Chapter in Wood, P. J., D. M. Hannah, and J. P. Sadler, eds, *Hydroecology and Ecohydrology: Past, Present, and Future,* John Wiley & Sons, Ltd. Accepted for publication

A Mathematical and Conceptual Framework for Ecohydraulics

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INTRODUCTION

The basic premise underlying ecohydraulics is deceptively simple – to meld together basic principles of biology and ecology (for brevity, both biology and ecology will be collectively termed ecology from here forward) and hydraulic engineering. However, different disciplines can have very different traditions and conventions. This is particularly true for hydraulic engineering and ecology. For example, many conventional engineering tools trace their origin back to the conservation principles of Newton (i.e., conservation of mass, momentum, and energy), whereas many ecological tools trace their origin to Malthusian population growth and the ideas and concepts of Darwin. While there are many classroom and research examples of how the concepts of Newton can be integrated into ecology (e.g., Vogel 1983; Pennycuick 1992), the schism between engineering and ecology largely remains in water resources management tools and continues to impede the integration of hydraulic engineering and ecology into the new discipline of ecohydraulics. Reconciling this schism is the theme of this chapter.

The need to accommodate disparate traditions and to study processes that vary over wide ranges of spatial and temporal scales separates ecohydraulics from other disciplines and could be an impasse that prevents its further development. The different approaches of hydraulic engineers and ecologists: 1) are historically applied to processes that differ substantially in spatial or temporal scale; 2) can be traced to different modeling traditions; and 3) utilize different sets of mathematical formulations, concepts, and assumptions. The full promise of ecohydraulics modeling and analysis may remain elusive because of the difficulty in reconciling the separate scale ranges that hydraulic engineers and ecologists each use to study the world. This difficulty has two consequences best expressed as two interrelated questions:

- First at a science level, how can researchers develop fundamental principles for ecohydraulics and thereby advance this field as a discipline when the underlying principles of its component disciplines appear so disparate?
- Subsequently at a practical level, how can resource managers implement sustainable development and biodiversity preservation that depend, ultimately, on an accurate understanding, integration, and forecast of the causal relationship between changes in the physico-chemical environment (the focus of engineers) with response of individuals, populations, and communities (the focus of ecologists) without developing such fundamental principles?

The way forward may lie in the recognition that processes associated with each different hierarchical level of an ecosystem also have associated scale ranges (Levin 1992). Neither the traditions nor conventions of engineers and biologists separately can adequately describe the different processes operating over the entire range of scales that typically characterize ecosystem dynamics and natural complexity. Neither discipline by itself can address discontinuity and mismatch of scales at which hydraulics are typically modeled with scales at which fish respond to their environment (Kondolf et al. 2000, Bult et al. 1999, and Railsback 1999). Therefore, a conceptual or mathematical bias is introduced when either engineering or biology is used by itself to represent the dynamics and complexity of an aquatic ecosystem. For example, ecosystem processes may vary in temporal and spatial scale from fine-scale hydrodynamics associated with habitat selection by stream macroinvertebrates, to intermediate scales associated with chemical transformations typical of water quality dynamics, to large-scale biological population dynamics in which one cycle may last decades and extend over thousands of kilometers. Although importance of scale is known, there are limited approaches to quantitatively include scale as a metric to describe ecosystem processes (Nestler and Sutton 2000) even though scale-associated issues are known to substantially affect forecast accuracy and reduce usefulness of single-discipline models for decision-making (Nuttle 2000).

It is in this science gray zone between engineering and ecology that the new interdisciplinary field of ecohydraulics is emerging. Ecohydraulics offers the promise to span the tools, concepts, and traditions of its two component disciplines. By so doing, this new discipline can address many of the most important resource management issues facing the world. However, before the new field of ecohydraulics can be elevated to the same stature as its more established components of ecology and hydraulics, it is first necessary to develop a scientific foundation for ecohydraulics comprised of guiding, fundamental principles. Simply applying standard hydraulic engineering tools to address ecological issues is an insufficient theoretical basis for ecohydraulics and will not support the development of ecohydraulics as a separate discipline. Ecohydraulics must be built on a scientific "common denominator" that allows hydraulic engineering and ecology to be melded together into a new discipline.

The objectives of this chapter are to: a) provide a brief historical background on ecohydraulics, b) provide a suite of unifying concepts that can be used by both ecologists and hydraulic engineers so that each can better understand the field of the other, c) relate natural processes to an appropriate modeling approach used either by engineering or ecologists, and d) illustrate how hydraulics and ecology can be integrated using two examples. These organizing concepts can be employed to couple existing tools of ecologists and hydraulic engineers to provide a parsimonious and useful representation of aquatic ecosystems that may describe natural complexity at extreme ends of spatial or temporal scales. By so doing, a firm foundation can be created upon which the discipline of ecohydraulics can be built.

ECOHYDRAULICS: WHERE DO THE IDEAS COME FROM?

The ideas underpinning ecohydraulics can be traced to two separate beginnings, one centered in hydraulic engineering and the other centered in ecology. Ecologists in academic settings have a long history of studying the relationship between fluid flow and ecological response (e.g. Ambühl 1959). This history is elegantly presented and reviewed by Vogel (1983) in his book "Life in Moving Fluids". Every student of either aquatic ecology or hydraulic engineering should read this book to understand the importance of fluid dynamics to aquatic biota at a first principles level. Since this book was first published there are many examples in which ecologists worked with the relationship between flow fields and organismic response (Carling 1992; Pavlov et al. 2000; Smith et al. 2005). However, while scientifically interesting, these investigations remained primarily in the realm of academia and were seldom used to support water resources management and decision-making.

Hydraulic engineers first systematically attempted to include organismic response into their work during efforts to develop design criteria for fish passage facilities at dams. The body of work can be traced back about 300 years (Odeh 1999) with many of the most important works described in Clay (1961) and Clay (1995). Examples of an engineering approach to fish passage include Bell (1973), Powers and Osborne (1985), and Bell (1991). However, these studies tended to treat fish as engines that exhibited different categories of swimming performance important to passage design. As fish passage technology studies became more multi-disciplinary, ecologists working primarily in Europe began developing natural fish ways. Their efforts began to integrate principles of fluvial geomorphology; river ecology, population dynamics, and behavior to supplement development of hydraulic design criteria (e.g., see works in Jungwirth et al. 1998, and Newbury and Gaboury 1993). However, the detailed understanding of the movement strategies used by fish to "hydro-navigate" through the river in search of different habitats was beyond reach.

The second major pathway in which hydraulic engineering contributed to ecohydraulics was through the development of aquatic habitat assessment methods as exemplified by the Instream Flow Incremental Methodology (Bovee) and similar methods. This methodology was an outgrowth of stream gauging techniques (Pierce 1941; Viessman and Lewis 1996) that divides the river into cells and allows the calculation of discharge. The analysis was performed by relating average depth, average velocity, and cover in each cell to previously determined habitat suitability curves. Cell specific values of habitat were then integrated over time and space to describe habitat dynamics of target species as part of assessing the effects of different flow alternatives. This methodology was widely applied but often criticized for its lack of biological realism because it relied so extensively on engineering and hydrologic methods.

The general lack of success in developing fish passage technology based solely on simple hydraulic parameters, like average velocity and average depth, is mirrored by the criticisms faced by users of aquatic habitat assessment methods. Increasingly, there is interest in closing this gap between hydraulic engineers and ecologists as both disciplines increasing understand their own limitations. In both cases, critical reviewers bemoan the lack of "first principles" to underpin the development of new tools and new concepts in fish passage and improved habitat assessment methods.

REFERENCE FRAMEWORKS OF ENGINEERING AND BIOLOGY

As disciplines, hydraulic engineering and ecology can be decomposed into "first principles" by progressively reducing their concepts until they are irreducible (*sensu* Aristotle 350 BC). Identifying first principles of the two disciplines should lead to the scientific common denominator that can be used to integrate them together to generate the new discipline of ecohydraulics. Mathematical models are abstractions of the guiding traditions and conventions of any discipline and, therefore, an examination of the attributes of their respective models should point to a discipline's first principles. The most fundamental attribute of a mathematical model is the manner in which it represents space-time and scale (Nestler et al. 2005). Three modeling reference frameworks are typically encountered in hydraulics and ecology each of which deals with space-time and scale differently: Eulerian, Lagrangian, and Agent (Goodwin et al. 2006). We know of no other frameworks for handling spatial and temporal dynamics of entities in ecosystems (Parrish and Edelstein-Keshet, 1999). Typically, one of these frameworks is used by itself to formalize and simulate natural processes, although features of the environment are inherently neither Eulerian, Lagrangian, nor Agent. As described below, each framework has specific strengths and weaknesses and appears to be optimally suited to address certain ranges of scale relative to the size of the physical domain to which the model is applied (Goodwin et al. 2006). These frameworks embody the fundamental principles underpinning hydraulic engineering and ecology and we believe an understanding of them is necessary to continue the evolution of a concept set that can serve as the theoretical and mathematical foundation for ecohydraulics.

Eulerian Reference Framework

In this framework the physical domain is discretized into a fixed mesh of interconnected compartments or cells (Figure 1A). Using established conservation equations, mass, energy, and momentum are transported through the grid and balanced at compartment interfaces (Thomann and Mueller 1987, Cassell et al. 1998). The Eulerian framework is useful for simulating processes occurring over times and distances that are short, compared to time and distance intervals used to update transfers across cell boundaries. The Eulerian framework is typically used when entities of modeling interest are very small in size relative to the physical domain of the system. Such processes can be averaged across an individual grid cell and their products transported passively by fluid flow without propagating substantial error. For example, bulk flow of water depends on molecular properties such as density and viscosity, which vary with temperature. Over the discrete time and distance intervals commonly employed with environmental models, variation of fluid properties are sufficiently gradual that they can be averaged into control volumes. Although larger scales must be considered, they are typically addressed as boundary conditions or initial conditions and not addressed in the governing equations. The Eulerian framework has also proven useful for simulating lower trophic levels (e.g., Gin *et al.* 1998) that are defined by short temporal and limited spatial scales.

Lagrangian Reference Framework

Lagrangian frames are preferable to Eulerian frames when aggregation of constituents into control volumes results in unacceptable accumulation of error. This typically occurs when entities of modeling interest exhibit dynamics that are intermediate or large in scale relative to the physical domain of the system. Lagrangian schemes retain individual identities of constituent particles or discrete volumes (both referred to as "particles" for brevity) and track them separately as they move throughout the computational grid (Figure 1B). The Lagrangian reference frame imposes no conservation principle other than the preservation of particle identity. Therefore, conservation principles, if required, must be imposed as additional constraints on the model system (Parrish and Edelstein-Keshet 1999, Gravel and Staniforth 1994). The movement of fish eggs in a stream or drogues in a flow field is best represented using the Lagrangian framework.

Agent Reference Framework

The agent framework is required when an entity of interest exhibits complex behaviors in response to its internal state or external signals (Figure 1C). This integration of internal state, external signals, and resultant complex behaviors cannot be represented adequately with either the Eulerian or Lagrangian frameworks or a combination of the two. Ideally, such entities are best represented using all three reference frameworks together. A simple example is a fish holding position in a river to feed. Its perception of the flow field is best defined using a Lagrangian frame (based on its specific location in the flow field) but its habitat (a block of water with uniform hydraulic conditions within which it occurs) is typically defined by a Eulerian frame. The fish's impetus to move depends on its internal state, typically a time varying trade-off between the need to feed and avoid predators, and the signals that it acquires providing information about the condition of its immediate surroundings. Fundamental to an agent framework is the concept of memory in which past events determine how the agent will respond to its present surroundings. In such a setting, the governing equations used in the Eulerian or Lagrangian frames are inadequate to describe the dynamics of this class of entity. Instead, the entity must be represented with its own separate set of governing equations. In ecological settings, detailed population dynamics or movement behaviors of organisms such as fish in aquatic environments or moose in terrestrial environments are typically simulated using individual-based models (IBM), a type of agent-based model.

DEFINITION OF AND CONCEPTS FOR ECOHYDRAULICS

Definition

Ecohydraulics should be an integrated discipline that honors the conventions and traditions of both ecologists and hydraulic engineers. It should recognize that the two component disciplines of engineering and ecology have different concepts and approaches and that each focuses on certain processes over limited ranges of scales. We believe these differences can be distilled to the dominant reference frameworks used by each of the two component disciplines (Nestler et al. 2005). To be elevated to the same stature as either aquatic ecology or hydraulic engineering, ecohydraulics must integrate the approaches of the component disciplines and through the resulting synergy develop new tools and approaches that are presently beyond the reach of either ecology or hydraulic engineering separately. We propose that the specialized goal of ecohydraulics should be to "integrate hydraulic and biological tools to improve the analysis and prediction of ecological response to physicochemical change in aquatic settings in support of water resources management".

A Mathematical Framework for Ecohydraulics

If the goal of ecohydraulics is to accurately relate biotic response to the physicochemical environment, then the predominantly Eulerian world of engineering must be reconciled and integrated with the predominantly Lagrangian/agent world of biology. To this end, we propose that ecohydraulics be founded on the concept of integrated reference frameworks. A quantitative method to implement this concept is the Eulerian-Lagrangian-agent Method (ELAM). In their fullest embodiment, integrated reference frameworks take advantage of the strengths of each of the reference frameworks described above to create a single, unified knowledge base in which information can be rotated, translated, or transformed to meet the information needs of any of the three reference frameworks. In such a framework, spatially and temporally incremental physicochemical information (such as hydraulics or water quality information) is stored in an Eulerian framework at discrete points within the grid (mesh).

However, individual organisms exist in continuous time and space and make directed movements or execute other behaviors based on cues and gradients in important stimulus variables and their internal state. The mismatch between incremental and continuous space-time must be addressed before ecology and hydraulic engineering can be integrated. To bridge the gap between the information needs of individual or groups of biota and the way information is stored in an Eulerian framework, interpolation methods can be used to shift information to spatial points of interest that do not fall on grid points where Eulerian information is stored. Once information has been shifted, agent-based methods can be used to describe how individual organisms such as fish or shell fish interface with the physico-chemico environment (Figure 1C) or with other individual organisms of their own species or other species. In this unified scheme, the Eulerian framework is the domain of the hydraulic engineer and the agent framework is the domain of the ecologist. The Eulerian and agent frameworks are linked together via the Lagrangian framework (Figure 2).

Integrated reference frameworks can be used to address a wide variety of simulation challenges because each frame can be applied at the scale for which it is best suited – the ideal foundation for ecohydraulics where two apparently divergent sets of concepts and tools must be integrated. We offer two complementary example applications of integrated reference frameworks to illustrate how engineering and biological models can be coupled together to create a greater synthesis. The first example implicitly couples the Eulerian and Lagrangian frameworks to create a hydraulically realistic description of fish habitat selection. The second example is the Numerical Fish Surrogate (NFS) (Goodwin et al. 2006) which illustrates a complete coupling in which all three reference frameworks are explicitly integrated into one system. The NFS is an example of an integrated reference frameworks model based on ELAMs and exemplifies a single, integrated knowledge engine in which information can be rotated, translated, converted, or rescaled, as needed, to be used by any one of the frameworks.

TWO EXAMPLES OF ECOHYDRAULICS

Example 1: Semi-Quantitatively Describing Habitat of Drift Feeding Salmonids

Background

While many factors can impact abundance of salmonids in streams, hydraulic pattern is often the first feature of a stream to be simulated and analyzed. Drift feeding salmonids occupy a focal position located in relatively low velocity water adjacent to a faster reach of stream. From the focal position, a fish can dart out into the faster current to feed. This behavior allows the fish to have the bio-energetic benefits of swimming in slow water while having access to the increased food delivery rate of fast water. Although this conceptual model is widely applied, rarely has it been noted that it is an inherently shear based description of habitat occupancy. Most habitat analyses are based on an Eulerian representation of the flow field in which average velocity is measured at the focal position of the fish (a Lagrangian representation), or at some arbitrary point in the water column near the fish. The result of this Eulerian-Lagrangian conceptual mismatch (i.e., an average cell velocity used to characterize a point location) is that hydraulically based habitat descriptions are unable to replicate the distribution of fish in streams and therefore cannot predict changes in abundance as a function of changes in hydraulics. This, despite the fact that juvenile salmonids occupy reach scale geomorphic features such as riffles, pools and runs with differing hydraulics in different densities.

Approach

The following procedures reconcile the reference framework mismatch and illustrate how integrated reference frameworks concepts can be used to guide a relatively simple hydraulic habitat analysis. We consider this procedure to be an excellent example of a semi-quantitative ecohydraulics approach in which hydraulic habitat analysis is integrated with biologically-based fish behavior. Microhabitat data from the Yakima River, Washington State U.S.A. (Allen 2000) was used to calculate the exposure strain rate (Neitzel et al. 2004) of juvenile Chinook salmon. An example of using a shear based approach to describing habitat (Figure 3) is found Smith et al. (in review). The exposure strain rate (e) is

$$e = \frac{\partial \bar{u}}{\partial y}$$

where $\bar{u}$ is the average water velocity (cm/s), and y is the characteristic length (cm), resulting in e having units of cm/s/cm. The characteristic length was taken to be 0.4 cm, or the minimum head width of fish observed during the study. A common characteristic length is needed to allow comparisons between all calculated values of e.

Results

Qualitatively, the exposure strain rate describes the Lagrangian conceptual drift feeding model using a metric (strain) that has physical meaning and maps back to an Eulerian habitat representation. The exposure strain rate was calculated for three seasons (spring, summer, and fall) and five reach scale geomorphic habitat types: deep pools, deep runs, low gradient riffles, run glides, and shallow pools. Microhabitat characteristics were measured through direct observation and sample sizes ranged between 241 and 393 fish. In each habitat type, three types of exposure strain rates were calculated. The vertical strain rate was calculated as the difference between the focal velocity and the mean column velocity measured 0.6 tenths from the surface. Two lateral strain rates were calculated as the difference between the focal position average velocity and the mean column velocity 0.6 and 1.2 m toward the center of the channel.

It was thought that a high or low strain rate would represent poor quality habitat since if the velocity gradient was high, a fish darting out to feed would be swept downstream and thus have to struggle to regain its former focal position or acquire a new one. Conversely, a focal position with a low strain rate might represent a location where food delivery rates were low. Therefore, the vertical strain rates should fall in a fairly narrow range for a given size class of fish. Statistical analysis supported the hypothesis that vertical strain rates were similar across the range of reach scale habitat types. In other words, juvenile Chinook salmon were occupying focal positions that have similar velocity gradients across all habitat types. A deep pool focal position was similar to a low gradient focal position in terms of strain rate. The lateral strain rates calculated at 0.6 and 1.2 m from the focal positions showed differences in strain rate. Deep pools lateral strain rates were lower than low gradient riffles.

Significance of the Example

This approach to describing habitat use is consistent with the biological model of drift feeding; however it is different than the normal application of strain rate to describe rivers. For example, strain rates measured from the focal position for the fish increase as distance from the fish increases meaning that average velocity increases over the distance between the two measurement points. If, however, strain is calculated on smaller scale strain rates decrease moves away from the boundaries, and increase moving closer to the boundaries. Since most of the fish observations were near the boundary it is possible that variation of strain rates integrated over the fish length serve as guidance for drift feeding fish seeking suitable focal positions.

There are three conclusions that can be drawn from this. First, focal positions are statistically similar in terms of a velocity gradient across different habitat types. This implies that fish were selecting focal positions independent of reach scale habitat. Second, velocity gradients were different between habitat types at scales of 0.6 and 1.2 m. Taken together, it appeared that juvenile Chinook were selecting focal positions with similar levels of shear independent of overall reach scale hydraulics associated with different reach scale habitats. Third, that by conceptually integrating the separate approach of the engineer and biologist in this example, a new insight was gained that could not have been obtained from the exclusive use of one of the disciplines.

Example 2: Quantitatively Describing Fish Swim Path Selection in Complex Flow Fields

Background

Hydropower dams on the Snake and Columbia Rivers in the Pacific Northwest of the USA block the out-migration of juvenile salmon (migrants). Bypass systems are constructed to intercept as many of these fish as possible and thereby prevent them from entering the turbines where they can be potentially injured or killed (Figure 4). To work effectively, migrants must be attracted to the vicinity of the bypasses and the hydrodynamic characteristics of bypass entrances must encourage the entry of migrants. However, the hydraulic design criteria for neither the approach nor entrances were known leading to the construction of large, expensive systems of variable performance with concomitant negative impacts on migrants.

Approach

The Numerical Fish Surrogate (NFS) is an example of how the three reference frameworks can be integrated together into a single consistent mathematical tool to address a problem that is presently beyond the reach of either hydraulic engineers or biologists (Goodwin et al. 2006). The NFS integrates the three reference frameworks. The Eulerian reference framework is represented by a Computational Fluid Dynamics model that outputs hydraulic information at 1.5 million nodes to describe the flow field in the dam fore-bay (immediately upstream) that is encountered by migrants approaching the dam. The Lagrangian framework is represented by the passive particle traces made by interpolating information from the nodes of the CFD grid to points that represent the path made by a neutrally buoyant passive particle. The Agent framework is represented by the behavior rules that can be applied to the passive (“dumb”) particles that allow them to acquire information from the CFD grid, to have a memory to help define their inner state, and to use process information from the environment relative to its inner state as the basis of swim behaviors (become "smart" particles) (Figure 5). The parameters of the behavioral model can be recursively adjusted to minimize the difference between traces made by virtual and real fish. By interpreting the best behavioral rules, it is possible to gain insight into the hydraulic navigation strategy of real fish, how fish use hydrodynamic cues to make movement decisions, and to improve dam design and operation to minimize impacts on fish.

Results

NSF forecasts generally match observed passage proportions with goodness of fit (slope/R-square) decreasing from spillway (0.95/0.85), bypass (1.07/0.80), to powerhouse (1.15/0.61). The reduced goodness of fit for the powerhouse is likely related to the difficulty of maintaining constant operation of the powerhouse during the collection of fish tracks. Total powerhouse discharge usually remains constant, but the units in operation and the distribution of load across those units typically changes during a test. The CFD model however, is run at steady-state and consequently does not capture changes in operation. Spillway operation is held constant during a test and therefore meets the steady-state assumption. Bypass system operation is also held constant, but its location nearer the powerhouse than the spillway for most cases reduces its goodness of fit. The "rules off" case represents passive transport. Therefore, the improvement in goodness of fit provided by the "rules on" case represents the contribution of the behavioral rules towards the quality of the forecast.

The "traffic rule" used by migrants only makes sense in the context of fluvial geomorphology of free flowing rivers (Figure 6). The relationship between hydraulic strain and velocity is best understood using principles of fluvial geomorphology. In free flowing rivers, flow field pattern results from flow resistance (Leopold et al. 1964). Without flow resistance there is no force to distort a unit volume of water once it is set into motion by the force of gravity (Ojha and Singh 2002). Flow resistance can be separated into two categories for sub-critical, steady flow: friction resistance and form resistance. Friction resistance in a simple, straight, uniform channel produces a flow pattern in which average velocities are lowest nearest a source of friction (such as the channel bottom and edges) with a zero water velocity occurring at the water-channel interface. Pattern in the strain field is the inverse of pattern in the velocity field, with lowest strain occurring furthest from a source of friction resistance and highest strain occurring nearest a source of friction resistance.

Form friction is created by large woody debris or rock outcrops projecting into the channel. As in the case of friction resistance, strain rate associated with form resistance increases towards the signal source. In contrast to bed friction (where water velocity decreases towards the friction source), water velocity increases towards the signal source for form resistance because of local reduction in conveyance area and increased travel distance of water flowing around an obstruction. A fish approaching a stump from the upstream direction will sense an increase in strain and an increase in water velocity magnitude until solid boundary effects very close to the obstruction are encountered. By integrating information between the strain and velocity fields, fish have sufficient information to separate channel structures associated with either friction or form resistance, thereby creating a hydrodynamic "image" of their immediate surroundings.

Significance of the Example

There are three significant findings from this work:

- The NFS can accurately forecast response of fish to the hydrodynamic fields created by different dam designs and operations allowing water resources developers to optimally design bypass systems and take other steps to minimize the impact of water resources development on out-migrating juvenile salmon. This tool could not have been developed using concepts restricted to either hydraulic engineering or ecology.
- In natural, free flowing rivers there is a dynamic equilibrium between flow field and bed form. Fish have acquired behaviors and sensing systems over geologic time to hydraulically navigate such systems. Unfortunately, flow pattern at dams is determined by size, orientation, and operation of gates, valves, and orifices and not a dynamic equilibrium between discharge and channel bed form. The creation of flow features, such as high energy intake plumes that are uncommon in free flowing rivers causes fish to become "confused" at dams when they apply behaviors to hydrodynamic cues evolved in free flowing rivers over geologic time to features at dams that do not exhibit this relationship. Dams can be designed that incorporate "natural hydrodynamic signals" into their design to reduce their impact on fish. By so doing, the hydraulic "foot print" of the dam can be minimized, perhaps even made invisible, to migrating fish with attendant benefits to society. This

solution to the vexing challenging of managing impacts of dams could not have been developed from either hydraulic engineering or ecology as individual disciplines.

- At an application level perspective, ELAM models like the Numerical Fish Surrogate address several needs in ecohydraulics approaches: (1) conversion of information from sources that differ in metric, range, scale, and dimensionality to a form of computer script (agents) that corresponds to animal perceptions (Bian, 2003), (2) ability to systematically organize and evaluate behavior hierarchies from the integration of information from various sensory modalities that may take varying precedence during the changing phases of a behavioral sequence (Sogard and Olla, 1993; New et al., 2001), (3) decentralized computer script for adding, eliminating, or modifying components without affecting the rest of the model (Ginot et al., 2002), (4) the theoretical and computational basis to elicit vector-based virtual movement of individuals responding to abiotic and biotic stimulus data provided in either Eulerian (Tischendorf, 1997) or Lagrangian form (Nestler et al., 2005), and (5) ability to easily compare model results to field-collected data (Hastings and Palmer, 2003).

DISCUSSION

An Opportunity for Engineers and Ecologists:

Tools that can be used to understand and forecast natural complexity and preserve biodiversity are a major challenge in water resources development. The concept of integrated reference frameworks is a theme that can be used by both hydraulic engineers and ecologists to build tools to address the challenge of sustainable development. For engineers, this concept leads to new areas for technology growth and new applications of established tools. For ecologists, the concept allows them to respond to the criticism that they have "physics envy" because their concepts often do not clearly and unequivocally lead to specific mathematical formulations, as is the case for many physics and engineering applications. Each discipline can expand into new areas of study and research and develop the tools that water resource managers require.

The concept of integrated reference frameworks allows engineering and ecology approaches to be integrated together either qualitatively to develop tools and understandings similar to that shown for the first example or highly quantitative tools similar to the second example that can be used to address difficult environmental water-related issues. The concept is flexible and can be used to integrate tools commonly applied in either aquatic ecology or hydraulic engineering. The significance of both examples lies in the fact that they are both built on integrated reference frameworks concepts and that without this foundation, neither example could be possible. In addition, the concept allows both hydraulic engineers and aquatic ecologists to better articulate the assumptions they make when schedule or funding realities limit their ability to utilize the full concept.

Integrated reference frameworks offer a number of advantages over single framework modeling approaches because of their ability to realistically simulate ecological processes that occur across a wide range of scales. ELAM methods allow the three frameworks to be mathematically coupled and conceptually integrated to accurately simulate processes that occur across a wide range of scales typically encountered in ecosystem analysis and simulation. ELAMs have the potential to partially address the problems identified by Alewell and Manderscheid (1998) that some biological processes are inherently too difficult to simulate and by Turchin (1997) that full spatiotemporal analysis is conceptually difficult. In particular, the Lagrangian module of ELAMS can be used to simulate animal movement behavior, a difficult but critical element in simulating and managing larger aquatic organisms because they often exhibit integrated responses to complex situations (Schilt and Norris 1997), well outside the simulation capabilities of Eulerian-based models.

Challenges and Limits for Ecohydraulics

Below we identify three of the challenges and limitations of ecohydraulics that can be the source of future research and development.

The challenge of the habitat mosaic: The habitat mosaic concept () used to characterize aquatic ecosystem dynamics requires that rivers be considered as dynamic patchwork of interconnected habitats that dynamically appear and disappear along the river corridor in response to flow and channel change. However, most of the tools used by both engineers and ecologists often requires the steady state assumption for flow and almost always assumes a rigid channel. In the future, ecohydraulics must embrace both the perspectives and tools used by river geomorphologists to more fully address river management issues such as short-term bed form variations, long-term reach-scale cycles of aggradation and degradation and channel variation all of which are simultaneously at play.

The challenge of multi-scale features. Almost all engineering tools used to describe channel shape use a relatively limited range of cell or mesh sizes and they assume that the Cartesian coordinate location of physical features within the channel is important. However, river channels are probably self-similar structures so that methods borrowed from fractal geometry (e.g., Nestler and Sutton 2000) may provide more accurate depiction of the structure of river channels that can be applied to better understand habitat dynamics for many different sized biota.

The challenge of the real world - budgets and schedules. Most resource managers are not interested in supporting lengthy, expensive, high resolution, academic investigations of streams and rivers. Instead they favor the application of relatively simple, fast, and inexpensive screening methods. We recommend that ecological model similitude analysis (Petts et al. 2006) be conducted to reconcile this tension between basic science and resource management. In this approach, high resolution, first-principles based studies are conducted to describe processes of interest. Once completed, the high resolution methods are progressively simplified by coarsening time and space scales, by simplifying equations through combing or eliminating coefficients, and by reducing dimensionality. Using a combination of sensitivity and divergence analysis, the high resolution methods are simplified until the answer they give differs substantially from the high resolution methods. The point immediately prior to divergence represents the simplest model that provides scientifically defensible output.

CONCLUSIONS

ELAMs realistically simulate ecological processes that occur across a wide range of scales and therefore integrate the tools and principles of multiple disciplines. For the example in this manuscript, the principles underlying the engineering computational fluid dynamics model were not compromised in any way to simulate the movement dynamics of salmon. Concomitantly, no guiding biological principles were compromised to accommodate the fluid dynamics simulation. Unlike single framework modeling approaches, ELAMs allow multiple, diverse disciplines to collaborate in a way that does not require any individual discipline to compromise its guiding principles. This capability can be expanded to include other modeling approaches in the future, such as individual-based models or geomorphology models, to develop ever more realistic tools to guide water resources planning and management.

In a practical sense, ecohydraulics as the discipline, and ELAM as the tool, integrates the point of view of the resource manager, who sees the habitat from the fixed perspective of the Eulerian framework and the point of view of the fish, which sees a varying world to which it must respond.

ACKNOWLEDGEMENTS

The authors thank the many colleagues whose ideas and concepts were freely shared over many years that culminated in the suite of ideas presented herein. We particularly acknowledge the contributions of Dr. Larry Weber and his students of IIHR Hydrosystems and Engineering, University of Iowa. We thank Dr. Jim Pennington and Ms. Toni Toney both of the U.S. Army Engineer Research and Development Center, Vicksburg, MS and two anonymous reviewers for their helpful comments and suggestions as well as the two anonymous reviewers. We would also like to thank Tracy Hopkins for her assistance with document and figure preparation. Permission was granted by the Chief of Engineers to publish this information. 3-D computer virtual fish animations and further information on Eulerian-Lagrangian-agent modeling (ELAM), including the Numerical Fish Surrogate, can be found at http://www.wes.army.mil/EL/emrrp/nfs/.

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Figure Captions

Figure 1. Scale relationships between the three reference frameworks. A. Symbolic representation of the Eulerian framework in which entities associated with small scales are aggregated into a control volume (cell) and simplified as cell volumes and fluxes. Note that particle identity is lost. B. Symbolic representation of Lagrangian framework where an entity (particle) exhibiting larger scale dynamics passively moves through a number of Eulerian cells. Such particles cannot be aggregated into cells without accumulation of substantial error and must, therefore, maintain their individual identities. The Eulerian 2-D cells are shown only for comparison. C. Symbolic representation of the agent framework in which an entity (A) moves through space and interacts with other agents (B) via rules that govern agent-agent interactions and agent-system interactions based on information acquired within the agent response envelop (cross hatched spheres).

Figure 2. Symbolic relationships between optimum reference frameworks and inherent entity scale attributes. Note hydraulic engineering methods typically (with exceptions) used in water resources management employ tools and concepts founded on Eulerian representations and that biologists and ecologists employ tools best classified as agent-based tools and concepts. Lumped parameter population growth models, competition models, and other types of ecological models designed to study biological populations can be envisioned as simplifications of agent-based frameworks.

Figure 3. Illustration of vertical and lateral strain rate velocity measurement points.

Figure 4. Aerial view of a typical dam illustrating powerhouse and bypass systems. RSW=Retractable Surface Weir; SBC=Surface Bypass Collector; BGS=Behavior Guidance System.

Figure 5. Comparison of observed and forecasted swim paths made by out-migrating juvenile salmon.

Figure 6. Pattern of the strain and velocity fields in a stream in cross section (A), profile, (B), and plan (C) views.

Figure 1

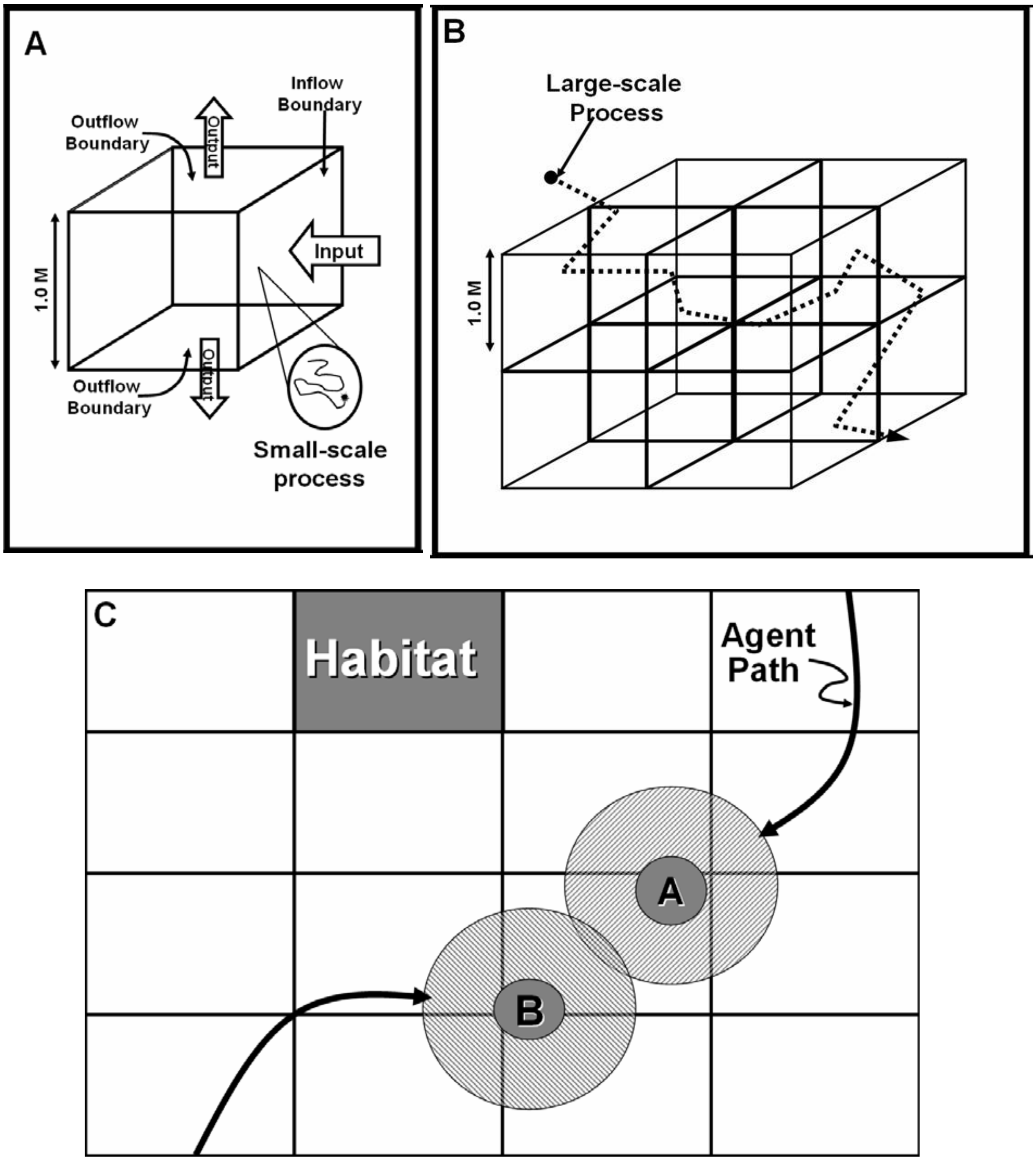

A
Inflow Boundary
Outflow Boundary
Output
Input
1.0 M
Outflow Boundary
Input
Small-scale process
B
Large-scale Process
1.0 M
C
Habitat
Agent Path
A
B

Figure 2

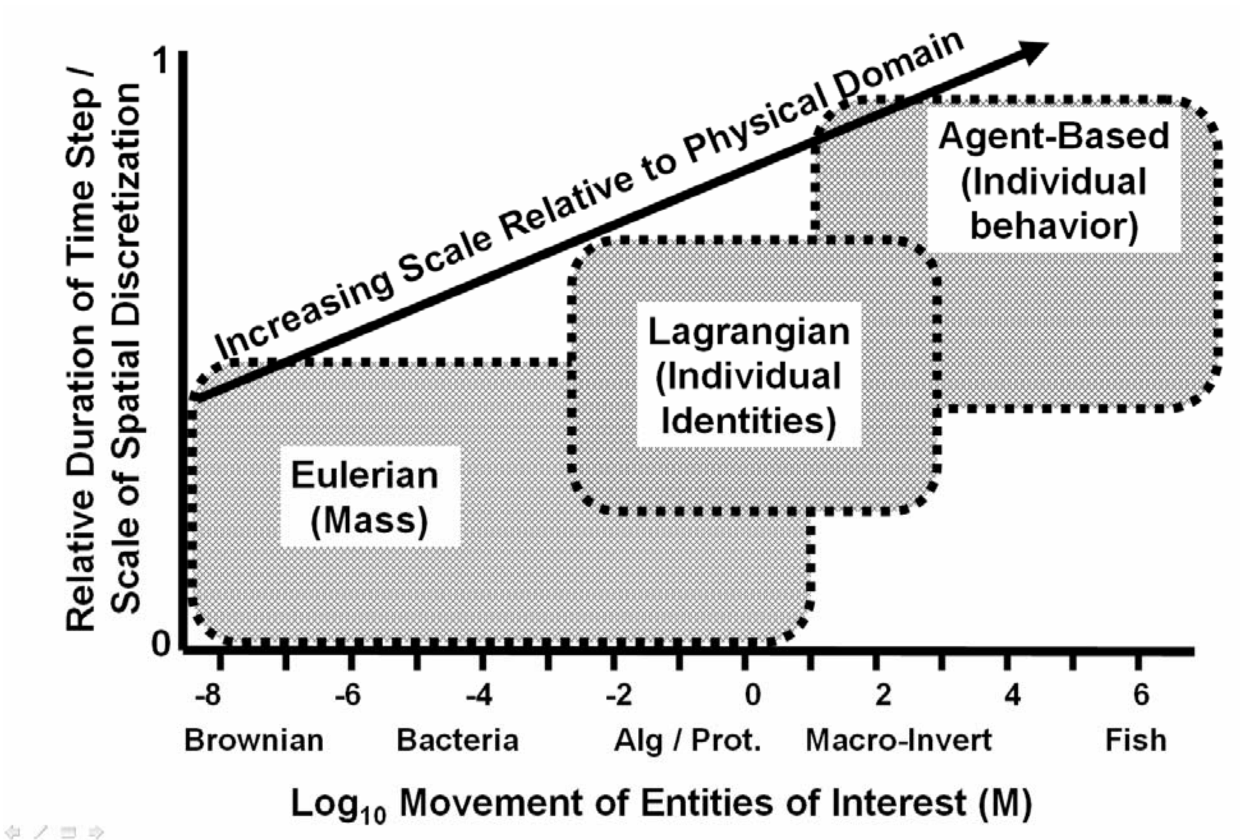

Increasing Scale Relative to Physical Domain
Relative Duration of Time Step / Scale of Spatial Discretization
1
0
Agent-Based (Individual behavior)
Lagrangian (Individual Identities)
Eulerian (Mass)
-8
-6
-4
-2
0
2
4
6
Brownian
Bacteria
Alg / Prot.
Macro-Invert
Fish
Log10 Movement of Entities of Interest (M)

Figure 3

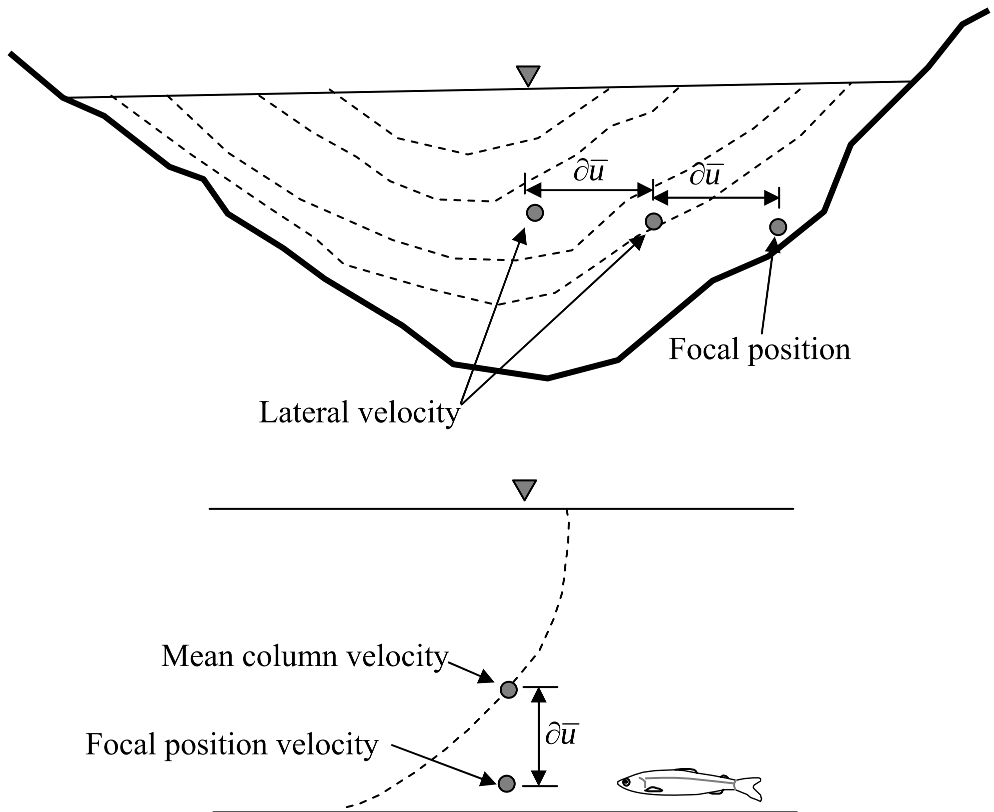

$\partial\overline{u}$
$\partial\overline{u}$
Focal position
Lateral velocity
Mean column velocity
Focal position velocity
$\partial\overline{u}$

Figure 4.

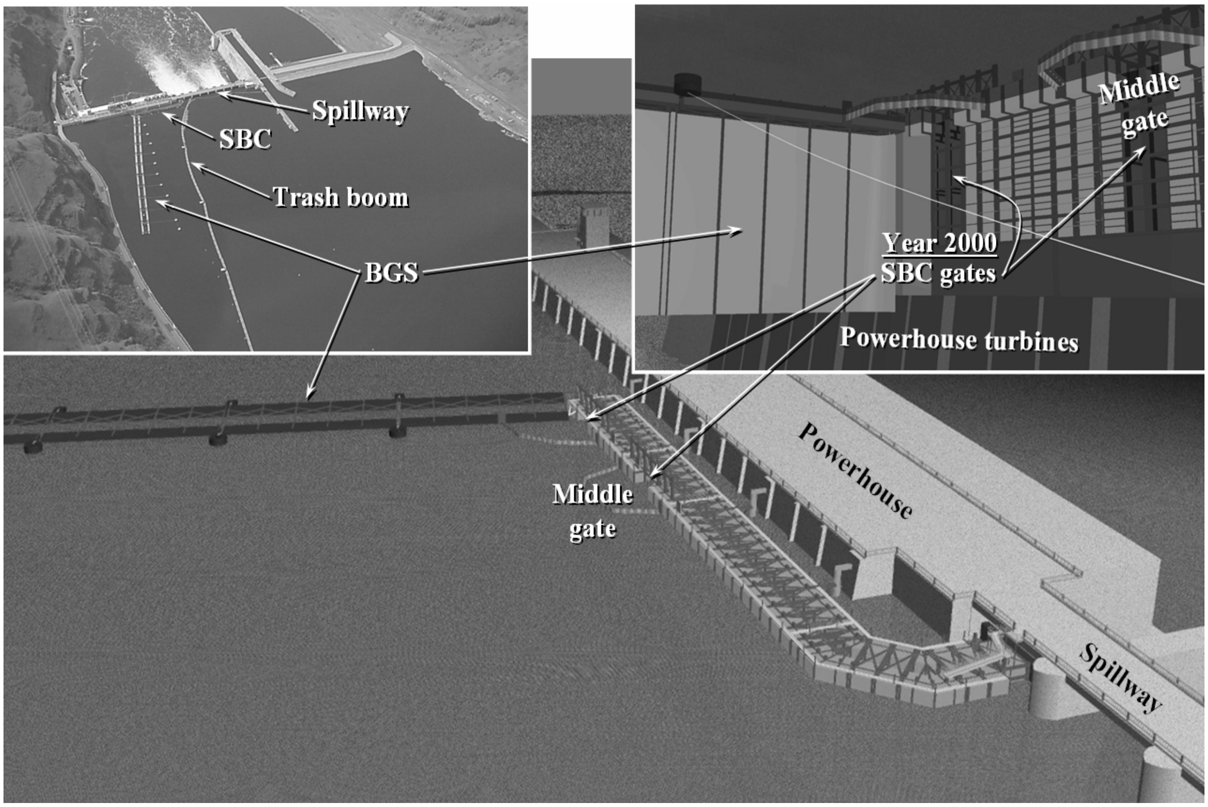

Spillway
SBC
Trash boom
BGS
Year 2000
SBC gates
Middle gate
Powerhouse turbines
Middle gate
Powerhouse
Spillway

Figure 5

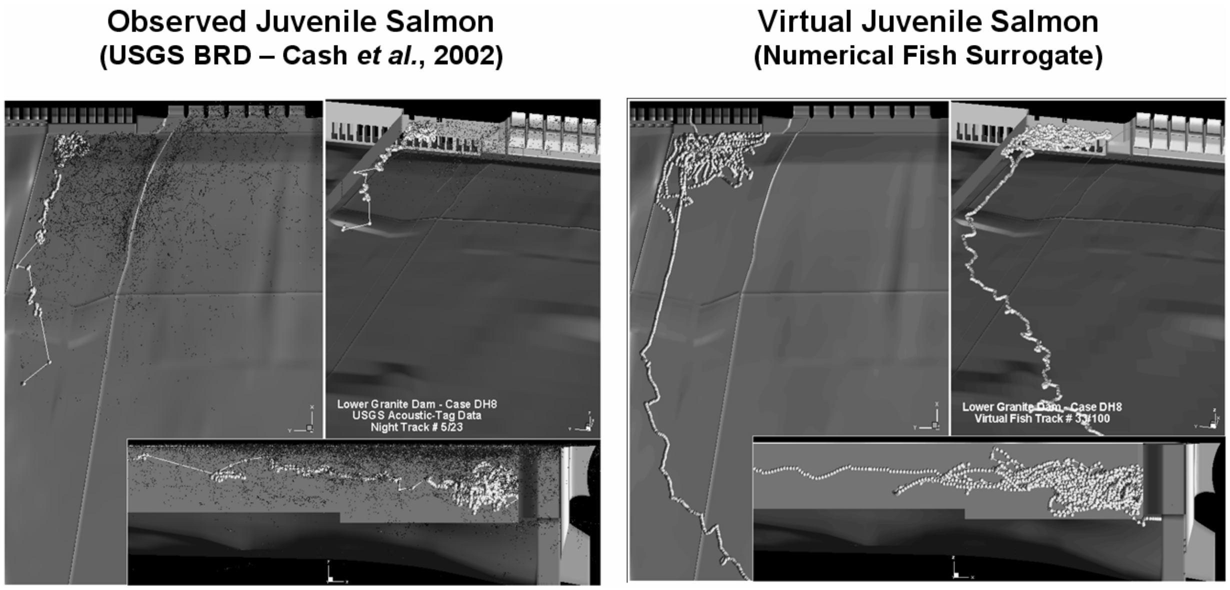
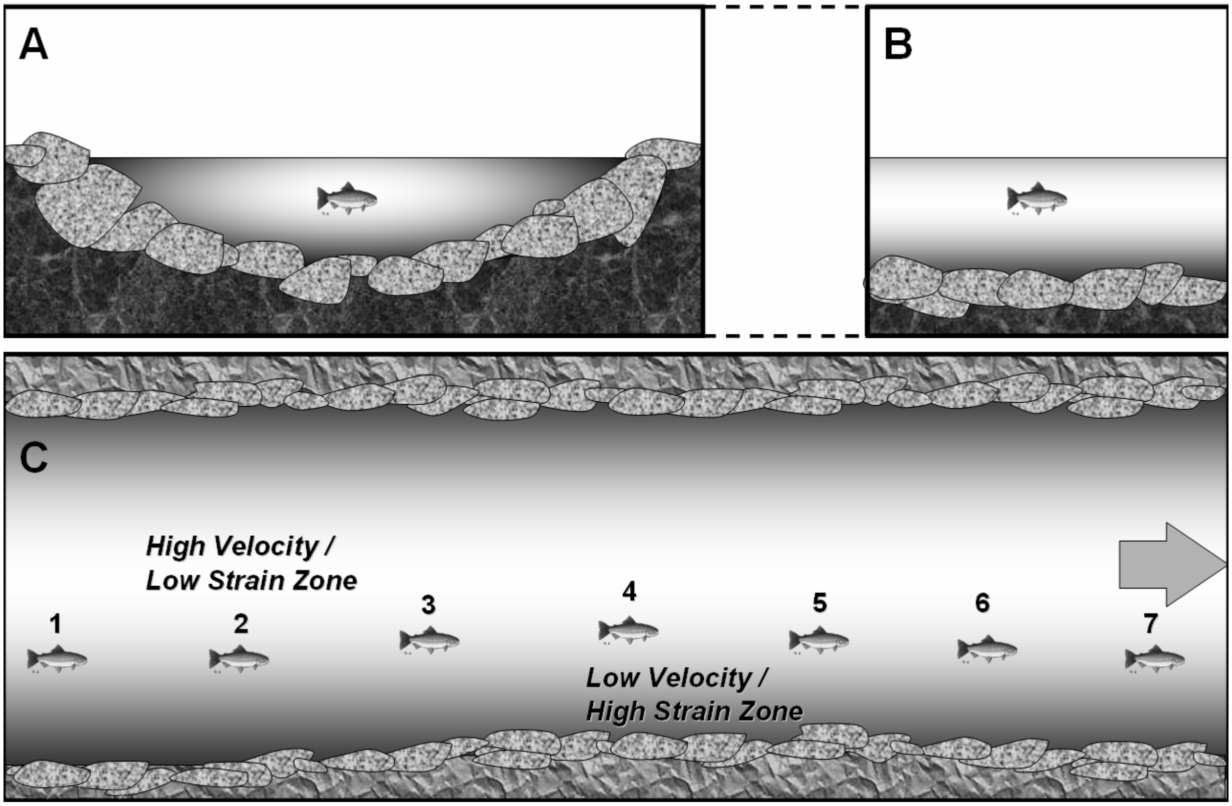

Observed Juvenile Salmon
(USGS BRD – Cash *et al.*, 2002)
Lower Granite Dam - Case DH8
USGS Acoustic-Tag Data
Night Track # 5/23
Virtual Juvenile Salmon
(Numerical Fish Surrogate)
Lower Granite Dam - Case DH8
Virtual Fish Track # 33/100

Figure 6


A
B
C
High Velocity /
Low Strain Zone
1
2
3
4
5
6
7
Low Velocity /
High Strain Zone